New Frontiers in the Solar System

An Integrated Exploration Strategy

Solar System Exploration Survey

Space Studies Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, N.W. • Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this project was provided by Contracts NASW 96013 and 01001 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsor.

International Standard Book Number 0-309-08495-4 (Book)
International Standard Book Number 0-309-50836-3 (PDF)

Cover design by Penny E. Margolskee

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, N.W.
Washington, DC 20001

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

SOLAR SYSTEM EXPLORATION SURVEY

Steering Group

MICHAEL J.S. BELTON, Belton Space Exploration Initiatives, *Chair*
CAROLYN PORCO, Southwest Research Institute, *Vice Chair*
MICHAEL A'HEARN, University of Maryland
JOSEPH A. BURNS, Cornell University
RONALD GREELEY, Arizona State University
JAMES W. HEAD III, Brown University
WESLEY T. HUNTRESS, JR., Carnegie Institution of Washington
ANDREW INGERSOLL, California Institute of Technology
DAVID JEWITT, University of Hawaii
JOHN F. MUSTARD, Brown University
ANDREW NAGY, University of Michigan
DIMITRI A. PAPANASTASSIOU, Jet Propulsion Laboratory
ROBERT T. PAPPALARDO, University of Colorado
MITCHELL SOGIN, Marine Biological Laboratory
THOMAS YOUNG, Lockheed Martin Corporation (retired)

Inner Planets Panel

CARLÉ PIETERS, Brown University, *Chair*
RONALD GREELEY, Arizona State University, *Vice Chair*
MARK BULLOCK, Southwest Research Institute
BRADLEY JOLLIFF, Washington University
ANN SPRAGUE, University of Arizona
ELLEN STOFAN, Proxemy Research

Mars Panel

JOHN A. WOOD, Harvard-Smithsonian Center for Astrophysics, *Chair*
JOHN F. MUSTARD, Brown University, *Vice Chair*
WILLIAM BOYNTON, University of Arizona
W. ROGER BUCK, Lamont-Doherty Earth Observatory
JOHN HAYES, Woods Hole Oceanographic Institution
KAREN MEECH, University of Hawaii
ANDREW NAGY, University of Michigan
KEITH NOLL, Space Telescope Science Institute
ROBERT T. PAPPALARDO, University of Colorado
ANNA-LOUISE REYSENBACH, Portland State University
J. WILLIAM SCHOPF, University of California, Los Angeles
ANN SPRAGUE, University of Arizona

Giant Planets Panel

RETA BEEBE, New Mexico State University, *Chair*
ANDREW INGERSOLL, California Institute of Technology, *Vice Chair*
AMANDA BOSH, Lowell Observatory
THOMAS HILL, Rice University
JULIANNE MOSES, Lunar and Planetary Institute
GERALD SCHUBERT, University of California, Los Angeles

Large Satellites Panel

ALFRED McEWEN, University of Arizona, *Chair*
ROBERT T. PAPPALARDO, University of Colorado, *Vice Chair*
CAITLIN GRIFFITH, University of Arizona
TORRENCE V. JOHNSON, Jet Propulsion Laboratory
KRISHAN KHURANA, University of California, Los Angeles
WILLIAM MOORE, University of California, Los Angeles

Primitive Bodies Panel

DALE CRUIKSHANK, NASA-Ames Research Center, *Chair*
MICHAEL A'HEARN, University of Maryland, *Vice Chair*
STANLEY DERMOTT, University of Florida
ALAN STERN, Southwest Research Institute
JOSEPH VEVERKA, Cornell University
MICHAEL ZOLENSKY, NASA-Johnson Space Center

Astrobiology Panel

JONATHAN LUNINE, University of Arizona, *Co-chair*
JOHN BAROSS, University of Washington, *Co-chair*
LUANN BECKER, University of California, Santa Barbara
STEVEN A. BENNER, University of Florida
JOSEPH A. BERRY, Carnegie Institution/Stanford University
WENDY M. CALVIN, University of Nevada, Reno
DAVID DEAMER, University of California, Santa Cruz
MARILYN FOGEL, Carnegie Institution of Washington
KATHERINE H. FREEMAN, Pennsylvania State University
J. PETER GOGARTEN, University of Connecticut
NORMAN PACE, University of Colorado
SANDRA PIZZARELLO, Arizona State University
DAVID A. STAHL, University of Washington
LUCY M. ZIURYS, University of Arizona

Staff

DAVID H. SMITH, Study Director
ROBERT L. RIEMER, Senior Staff Officer
BRIAN DEWHURST, Research Associate
SHARON S. SEAWARD, Senior Project Assistant (through December 2001)
RODNEY HOWARD, Senior Project Assistant (after January 2002)

SPACE STUDIES BOARD

Foreword

In 1957, on a dark hillside in Lincolnshire not far from the place where the young Isaac Newton grew up, I watched Sputnik travel inexorably across the twilight sky and was moved by the magnificence of it all. In the United States, the drama of the satellite's launch quickly led to the formation of the National Aeronautics and Space Administration (NASA) and the start of the exploration of the solar system. Forty-five years later, with millions of others, we have vicariously traveled to nearly every corner of the solar system and have learned how much more there is to discover and how imperfectly we understand the massive findings of past and current planetary missions and ground-based observations.

Exploration, discovery, and creative scientific research are the keys to new knowledge, and if we wish to know our origins and our destiny, whether we are unique or commonplace, and how nature governs our lives, we have no alternative but to explore the Sun's system of planets, satellites, comets, and asteroids to discover their secrets and understand the processes that make them what they are.

The exploration of the solar system is a technically challenging and expensive endeavor. Success is not always guaranteed, and tenacity and perseverance are required. Yet in the United States, as in some other countries, this challenge has been met with resolve. Today we are planning space missions that may tell us whether other life exists or has ever existed in places beyond Earth. We are engaged in research that probes from the very cores of planets to the atomic processes that occur in the highest regions of their atmospheres and plasma environments, and we are carrying out surveys to find potentially hazardous objects in near-Earth orbits that could affect the future of us all. Answers to some of the most profound questions—Are we alone? Where did we come from? What is our destiny?—may be within our grasp.

To continue this exploration in the most productive way, an effective strategy is needed that will produce the most significant results for the least time and resources spent. This is the purpose of the present survey, which was commissioned by NASA in 2001. It is to provide the scientific rationale for a ranked set of exploratory missions that could be launched in the coming decade. It must also integrate the wide range of interests—from atmospheric physics to geology and from cosmochemistry to astrobiology—of those engaged in this exploration. The survey is not an implementation plan; it is a durable strategy on which sound implementation plans can be securely based.

In February 2002, while the survey was in progress, a significant, if not pivotal, event occurred with the publication of the President's proposed budget for fiscal year 2003. The proposals in that budget for NASA's

Solar System Exploration program have excited planetary scientists for several reasons. These include the following:

- Strong support for continued Mars exploration and the line of small, competitively selected Discovery missions;
- Creation of a continuing line of competed, medium-class missions, to be called New Frontiers;
- Major new support for research and analysis programs; and
- Initiation of new in-space power and propulsion technology programs to lay the basis for advanced exploration missions in the more distant future.

As the reader will discover, this survey builds on the many positive aspects of the President's proposals.

This report is not intended to be read straight through. For those who seek a broad overview and a synopsis of the mission priorities and other recommendations, there is the Executive Summary. For ease of reading, the main text is presented in two parts that are self-contained and can be read separately.

Part One contains a broad survey of the subject, indicating what is known about the various classes of objects, current research directions and key scientific questions, and recommendations from the supporting panels to the Steering Group on appropriate mission strategies for the near future. Six survey panels, consisting of a total of about 50 leading scientists, contributed this extensive material, which is arranged in five chapters. These chapters should provide excellent reference material for readers who are interested in specific issues.

Part Two presents an integrated strategy for future exploration that was devised by the Steering Group using the material from the panels, together with direct inputs from the scientific community, NASA personnel, government and private laboratories, professional societies, and the interested public. This strategy is expressed in a short list of key scientific questions, a ranked list of conceptual missions that derive from these questions, and a series of recommendations for the decade 2003-2013. It is hoped that the reader will find the scope of this strategy as exciting and relevant as I do. The Steering Group anticipates that the cost of carrying it out is commensurate with the resources that are proposed in the President's 2003 budget. With unity of purpose, the mission plan that is presented in this document can be realized to the benefit of all.

Michael J.S. Belton, *Chair*
Tucson, Arizona
April 4, 2002

Preface

NASA's Office of Space Science (OSS) employs a relatively mature strategic planning process that relies heavily on input from the scientific community to establish the scientific basis and direction for its space- and ground-based research programs. The primary sources of this guidance are the independent scientific analyses and recommendations provided by reports of the National Academies, particularly those from the Space Studies Board (SSB). Using those independently developed science strategies as input, OSS then employs a roadmapping process that is carried out by NASA's internal committees, especially the Space Science Advisory Committee and its associated subcommittees.

This roadmapping process builds on the results of National Research Council (NRC) science strategies to define more detailed scientific objectives and investigations, as well as specific missions to address them. The roadmapping process factors in budget and technical aspects to refine the agency's portfolio of development options for the decade. The roadmaps constitute a major element of the triennial OSS strategic planning process, which in turn feeds into the overall NASA strategic plan that is revised every 3 years in compliance with the Government Performance and Results Act.

The last strategy for solar system exploration, the so-called Burns report,[a] was produced by the Space Studies Board in 1994. Since then, a number of important developments have led to the need for a new or substantially revised science strategy. These developments include significant changes in the way that NASA selects and manages its planetary exploration missions, with increasing emphasis on the "faster-better-cheaper" paradigm, and major new scientific results from a variety of spacecraft, including Lunar Prospector, Mars Pathfinder, Mars Global Surveyor, Galileo, Near Earth Asteroid Rendezvous, and Cassini. Moreover, since the publication of the Burns report, the SSB has produced more than a dozen relevant, focused, topical reports whose conclusions, integrated into a single, comprehensive strategy, would inform solar system exploration for the next decade.

Against this background, Edward J. Weiler, NASA's associate administrator for the Office of Space Science, requested that the SSB undertake a study designed to survey the current status of, and research strategies for, solar system exploration (see Appendix A). The study, outlined in letters sent to the SSB in January and April of 2001,

[a]Space Studies Board, National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994.

was to be modeled on the traditional astronomy and astrophysics decadal surveys.[b] In particular, the report resulting from the requested study should include the following components:

- A "big picture" of solar system exploration—what it is, how it fits into other scientific endeavors, and why it is a compelling goal today;
- A broad survey of the current state of knowledge about our solar system today;
- An inventory of top-level scientific questions that should provide the focus for solar system exploration today; and
- A prioritized list of the most promising avenues for flight investigations and supporting ground-based activities.

NASA's request also contained several important caveats regarding the ongoing Mars exploration and Discovery programs and suggested that the time scale to be covered should be approximately a decade. Further clarification from NASA indicated that the ranked list of ground- and space-based initiatives should be subdivided into a small number of cost categories.

The NRC subsequently appointed the Solar System Exploration Survey (SSE Survey), consisting of a 15-member Steering Group and supporting panels, to perform the study. Because of the wide range of scientific disciplines and the varied nature of the targets of solar system exploration, four ad hoc panels were established to advise the steering group on issues involved in the exploration of particular targets. These panels concerned themselves with issues relating to the inner planets, the giant planets, large satellites, and primitive bodies. Moreover, given the relative timing of this study and another study for NASA on Mars science and mission priorities being undertaken by the NRC's Committee on Planetary and Lunar Exploration (COMPLEX), it was decided to recruit the latter as the SSE Survey's Mars Panel and to limit the Inner Planets Panel's deliberations to Mercury, Venus, and the Moon. To provide a clear communication path between the various components of the SSE Survey, the panel vice chairs were also appointed to the Steering Group.

Soon after the beginning of the SSE Survey's work, it became clear that special arrangements were needed to understand any issues involving astrobiology, which is already a substantial element of supporting research at NASA. Since an existing NRC group, the Committee on the Origins and Evolution of Life (COEL), already had the necessary expertise, it was decided to recruit COEL as the SSE Survey's Astrobiology Panel.

The four ad hoc and two preexisting panels were asked by the Steering Group to prepare a broad survey of the current state of knowledge of those elements of solar system exploration within their purview. In addition, they were asked to list the key scientific questions and measurement objectives that they deemed appropriate for exploration in the period 2003-2013 and the foreseeable future. The panels were also invited to bring to the Steering Group a ranked list of possible flight missions and supporting ground-based activities that were appropriate for addressing the measurement objectives they had identified. The reports of the panels, suitably edited for consistent presentation, are included in Part One (Chapters 1 through 5) of this report. The various lists of key scientific questions and ranked lists of flight missions and supporting ground-based facilities from the panels were considered by the Steering Group and were used to formulate the SSE Survey's top-level, integrated list of scientific questions and recommendations for priority flight missions and supporting ground-based facilities. These are contained in Chapters 7 and 8 of Part Two. Finally, an analysis of the solar system exploration program, its strengths and weaknesses, and why it is a compelling endeavor today—that is, the "big picture"—was undertaken by the Steering Group itself and is contained in Chapter 6 of Part Two.

Solar system exploration has a broad professional community with diverse scientific interests; it is also an international endeavor involving mission, research, and instrument activities in many countries. In view of this diversity, it quickly became clear to the Steering Group and its panels that to successfully reflect the interests of this community and to achieve a broad consensus of opinion in support of the SSE Survey's recommendations, it

[b]See, for example, Board on Physics and Astronomy and Space Studies Board, National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

would be necessary to stimulate and consider a wide variety of inputs from the scientific community, from NASA and its advisory committees, from other government agencies (principally the Office of Management and Budget and the National Science Foundation), from major laboratories and research institutes (particularly the Jet Propulsion Laboratory, Johns Hopkins University's Applied Physics Laboratory, and NASA's Astrobiology Institute), and from the interested public through the Planetary Society. That these inputs should be treated with exceptional care and appropriate seriousness was obvious and became the consistent policy of the SSE Survey. Such inputs were solicited through oral presentations to the Steering Group and its panels, through teleconferences, through numerous public forums and town hall sessions at major community meetings, and by stimulating, through the good offices of professional societies, a series of 24 community-drafted white papers (listed in Appendix B) on a wide range of scientific subjects that covered essentially all aspects of solar system exploration. Mark Sykes, then the chair of the Division for Planetary Sciences (DPS) of the American Astronomical Society, undertook the responsibility of coordinating the timely generation of these papers and worked with the DPS, the Planetary Sciences Section of the American Geophysical Union, the Meteoritical Society, and the Geological Society of America to accomplish this.

This project was formally initiated at a meeting of the Steering Group held in Washington, D.C., on July 19-20, 2001. Work continued at meetings held in Irvine, California (November 14-16), and Tucson, Arizona (February 26-March 1, 2002).

In parallel with these meetings, the SSE Survey's four ad hoc and two preexisting panels held their own information-gathering and deliberative meetings at NRC facilities and major centers for research in the planetary sciences (e.g., Boulder, Colorado; Tucson and Flagstaff, Arizona; Mountain View and Pasadena, California; and Providence, Rhode Island). The Steering Group and the panels made extensive use of teleconferences, e-mail, and a password-protected Web site to facilitate their work.

Final drafts of the panel reports were completed in February 2002. The Steering Group assembled the first full draft of this report in March and held its final meeting in Washington, D.C., on March 26-28, 2002. The text was sent to external and internal reviewers in late April, was revised during May and June, and was formally approved for release by the NRC on July 2, 2002. This report was publicly released in an unedited, prepublication format on July 9. This, the edited text of the report of the Solar System Exploration Survey, was prepared during the latter half of 2002 and finalized in February 2003. This version supersedes all other versions.

The work of the SSE Survey was made easier thanks to the important help given by numerous individuals at a variety of public and private organizations. These include, in no particular order, Mark Sykes, Steven Larson, and members of the Committee of the Division for Planetary Sciences (American Astronomical Society); James Head III (American Geophysical Union, Planetary Sciences Section); Gero Kurat and Ed Scott (Meteoritical Society); Ralph P. Harvey (Geological Society of America, Planetary Geology Division); Charles Elachi, Firouz Naderi, Daniel McCleese, Martha Hanner, and Douglas Stetson (Jet Propulsion Laboratory); John Appleby, Andrew Cheng, Stamatios Krimigis, and Ralph McNutt (Applied Physics Laboratory); Bruce Betts and Louis Friedman (Planetary Society); Marc Allen, James Garvin, Colleen Hartman, Orlando Figueroa, Michael Meyer, Carl Pilcher, Guenter Riegler, and Jeffrey Rosendhal (National Aeronautics and Space Administration); Vernon Pankonin (National Science Foundation); and Steven Isakowitz and Brant Sponberg (Office of Management and Budget).

In addition, the following individuals greatly assisted the work of the Steering Group: John Brandt (University of New Mexico), Michael Drake (University of Arizona), Harald Hiesinger (Brown University), Bruce Jakosky (University of Colorado), Tim McCoy (Smithsonian Institution), Michael Mendillo (Boston University), Robert Millis (Lowell Observatory), Allan Tokunaga (University of Hawaii), and Roger Yelle (University of Arizona). Finally, the SSE Survey acknowledges the important contributions made by persons too numerous to mention who contributed to the community white papers listed in Appendix B, who made presentations at the SSE Survey's numerous meetings and public forums, and who assisted the Survey's work in other ways.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for

objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We wish to thank the following individuals for their participation in the review of this report: James Arnold (University of California, San Diego), Raymond Arvidson (Washington University), Radford Byerly, Jr. (University of Colorado), Anita Cochran (University of Texas), Riccardo Giacconi (Associated Universities, Inc.), Bruce Jakosky (University of Colorado), Melissa McGrath (Space Telescope Science Institute), William McKinnon (Washington University), Juan Pérez-Mercader (Centro de Astrobiología, Madrid), Mark Richardson (California Institute of Technology), Frederic Taylor (Oxford University), Alar Toomre (Massachusetts Institute of Technology), and James Van Allen (University of Iowa).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Thomas M. Donahue (University of Michigan) and Richard Goody (Harvard University). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents